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NBS SPECIAL PUBLICATION 664

U.S. DEPARTMENT OF COMMERCE/National Bureau of Standards

Gasification of Refuse Derived Fuel in a Paired Fluidized Bed Pyrolysis Unit

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Gasification of Refuse Derived Fuel in a Paired Fluidized Bed Pyrolysis Unit

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GASIFICATION OF REFUSE DERIVED FUEL IN A PAIRED FLUIDIZED BED PYROLYSIS UNIT

Results developed as part of the scientific exchange program of the respective governments of Japan and the United States

Prepared cooperatively by the Agency of Industrial Science and Technology, Ministry of International Trade and Industry, Government of Japan, Ebara Corporation, Japan (acting for the Government of Japan), and the National Bureau of Standards

Text prepared under the direction of Mr. S. Suzuki (AIST)
Text edited by Dr. Harvey Yakowitz (NBS)

Foreword

As part of the scientific interchange program initiated by the United States Government and the Government of Japan, the Department of Commerce was selected by the White House to be the pilot agency for a project concerned with resource recovery from discards originally destined for waste. Such discards include municipal waste and industrial waste. Under terms of the agreement signed by the President and the Prime Minister on May 2, 1980, the United States and Japan will exchange small teams of government scientists in order to examine resource recovery in the respective countries and to formulate possible joint research ventures.

The Office of Recycled Materials of the National Bureau of Standards (NBS/ORM), which was charged with fulfilling the duties assigned to the Secretary of Commerce by Subtitle E of the Resource Conservation and Recovery Act as ammended (P.L. 94-580; PL 96-482) was designated as the U.S. contact point for this project. The Japanese team visited the U.S. in December, 1981; NBS/ORM arranged the itinerary and provided technical briefings and an overview of resource recovery activities. At that time, NBS/ORM and Japanese representatives concluded an agreement for joint research to be performed as part of the project. The text is as follows:

AGREEMENT FOR JOINT RESEARCH JAPAN-UNITED STATES

Both sides agree to pursue item (1) proposed by Japan and item (2) proposed by U.S. to fullest extent possible:

(1) Gasification of Refuse Derived Fuel, RDF (Ebara Corporation)

AIST has been carrying out R&D involving dual fluidized bed gasification of the organic (plastic rich) portion of municipal refuse by operating a pilot plant at Yokohama, Kanagawa Prefecture, since 1973. The entire task has been carried out by Ebara Corporation under contract. This research is scheduled to be completed by the end of FY 1982 (March 31, 1982).

The U.S. is currently producing RDF from municipal refuse for possible use as substitute or supplemental fuel. If RDF could be converted into high quality gas in an efficient and economical manner, some beneficial application might be found, e.g., better market opportunities for waste-to-energy applications. Additionally, unwanted substances which are emitted by RDF in the course of its incineration may possibly be eliminated by gasification of RDF. It may be worthwhile to analyze the compositions of gas and other substances produced by the pyrolysis.

The experiment can be carried out at the said pilot gasifier in Yokohama. A specified amount (20 to 100 U.S. tons) of RDF will be transmitted to Japan for this purpose upon request of Japanese side. Data will be analyzed both in Japan and the U.S.

(2) Econometric models describing the market potential for various forms of recycled materials and energy from waste have been developed in the U.S. These models provide a basis for selecting the optimum resource recovery strategy for a region in terms of:

- o Markets available for the products
- o Technology selection
- o Size of plant
- o Transportation network
- o Refuse supply
- o Costs and revenues over the lifetime of the project

The data required for carrying out this analysis include:

- o Specifications for the products to be sold, e.g., heat value, residues produced, pollution properties, quantity produced per input ton of refuse
- o Size of plant
- o Efficiency of plant
- o Requirement of plant for energy and other operating costs
- o Requirement of plant for labor
- o Capital cost of plant
- o Lifetime of plant
- o Required treatment, if any, of input refuse
- o Type and amount of emissions and residues from plant

The U.S. undertakes to carry out market potential studies in several areas of the United States for any and all sets of data provided by Japan. Mutual benefits will be:

- o Japan learns if the processes and products being produced can be marketed in the U.S. profitably.
- o Japan learns direction for further research to improve processes and products in terms of marketability in the U.S.
- o U.S. learns whether Japanese technology can aid in dealing with solid waste management problems in various regions of the United States.

Both sides agree to further consider the attached lists of possible research items for possible action at a later time.

PROPOSED BY JAPAN

Possible Joint Research Items
(Japanese Government Institutes)

1. Combustion Studies of RDF or Other Solid Fuels (Government Industrial Development Laboratory, Hokkaido, AIST).

There is a 25 cm square fluidized bed combustion reactor now under test operation. Utilization of combustion heat by heat exchange is studied here.

In response to the U.S. proposal (3) (see overleaf) physico-chemical phenomena of combustion can be studied and some thermo-kinetic data may be obtained. RDF, coal, and other organic waste, or their mixtures can be burned in the reactor and emissions such as HCl, NH_3, CO, CO_2, and hydrocarbons can be monitored.

2. Utilization of Ash Residues from an Incineration Plant (National Chemistry Laboratory for Industry, AIST).

Treatment of ash residues from an incineration plant of municipal refuse is an important issue from the viewpoint of reducing the environmental burdens, and economically sound methods to reuse such ashes need to be found. Research involves effective classification of constituents in the ashes and utilization process development on reclaimed substances as well as effective design of the incineration system.

3. Acid Hydrolysis of Cellulose Materials (The same Laboratory as 2. above.)

It is necessary to find the most economical process which would convert waste or low cost biomass into ethanol. Enzymatic or acid hydrolysis process is first required to convert the cellulose fraction of raw material into glucose.

A two-stage batch reactor of acid hydrolysis originally designed is going to be examined.

PROPOSED BY UNITED STATES

Possible Joint Research Projects

1. Dusts created by the electric furnace process for the productionof steel contain valuable metal units. Economically sound methods to recycle such dusts on furnace-by-furnace basis need to be found. Research involves particle identification, classification and design of a system to separate out desired constituents.

2. Mill scales and sludges created by rolling processes in the steel industry need to be doiled for reclamation of metal units. Research involves characterization of such wastes and means to reclaim oils and/or energy plus metal units. Thermal and chemical processes need to be compared.

3. Combustion products created by burning refuse or mixtures of fossil fuels and refuse derived fuels need to be studied in order to prevent unwanted emissions, e.g., dioxin, and to provide for most efficient firing characteristics. Research involves setting up on-line monitoring for unwanted emissions and determination of basic thermokinetic data on the firing process. For example, co-firing of coal with refuse derived fuel reduces SO_x emissions drastically. The mechanism for this process should be deduced in order to optimize use of coal RDF mixtures for power boilers.

4. More economical means of recycling plastics from mixed wastes are needed. The Japanese are ahead of U.S. on the technology to do so. Joint research on new uses for waste plastics could be beneficial to the U.S.

5. The corrosion propensities of refuse and various forms of refuse derived fuels need to be studied. Joint research could aid in assuring that the potential for downtime or even failure of very expensive capital equipment is minimized.

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NBS

NBS/ORM arranged to ship to Japan about 35 tons of fluff RDF produced at the Baltimore County, MD resource recovery facility. This material arrived in Japan in early November, 1982.

In accord with the foregoing agreement, this RDF was gasified in a pilot scale resource recovery plant in Yokohama. The results of this gasification experiment are described in this NBS Special Publication. The text, as received from the Agency of Industrial Science and Technology of the Japanese Ministry of International Trade and Industry, was edited by Dr. Harvey Yakowitz, Chief, NBS/ORM.

Special thanks are given to the Text-Editing Facility of the National Measurement Laboratory of NBS for preparation of the final version of the report.

Abstract

The refuse derived fuel (RDF) produced at the Baltimore County Resource Recovery Plant and provided by NBS to the Government of Japan was gasified in a paired-bed pyrolysis unit, i.e., a fluidizing medium (sand) was circulated between a pyrolysis reactor and a combustion reactor. Thus, pyrolysis and combustion occur separate from one another; hence, the name "paired-bed."

The gas refining equipment consists of two chains, one for pyrolysis gas and the other combustion exhaust gas:

1. A cyclone separates char from the gas coming from the pyrolysis ~~pyrolysis~~ reactor. This char is fed to the combustion reactor for burning. After the gas passes through a heat exchanger and is quenched in a carbon deposit protector, a tar-separator removes oil mist and the gas is cleaned in a scrubber. A small portion of this clean gas is pressurized by a blower, preheated in a heat exchanger and used to fluidize the pyrolysis reactor bed; the remaining gas is sent to a tank for storage.

2. The exhaust gas generated by the combustion reactor is discharged into the atmosphere after being treated by means of a two-stage cyclone and electric dust precipitator. The non-combustible substances contained in the feed stock are discharged from the bottom of the combustion tower periodically.

The RDF was fed into the system at a rate of 0.6 to 1.0 tonnes per hour. The pyrolysis reaction temperature was about 650 °C. The following ultimate analyses were performed: (N.B. "T" is "Trace")

1. Feedstock

   a. Main components
      C, H, N, Cl, Na, K, Ca, Ash.

   b. Harmful components
      Cu, Pb, Cd, T-Hg, As, T-Cr, Al.

   c. Heat value

2. Pyrolysis gas components

   a. Main components
      H_2, O_2, N_2, CH_4, CO, CO_2, CmHn.

   b. Harmful gas components
      HCl, H_2S, NH_4, HCN, SO_x, NO_x.

   c. Heat value

3. Flue gas

    a. Main gas components

        O_2, N_2, CO, CO_2.

    b. Harmful components
        SO_x, NO_x, HCl, dust.

4. Ash

    a. Main components
        C, H, N, S, Cl, Na, K, Ca.

    b. Heavy metals
        Cu, Pb, Cd, T-Hg, As, T-Cr, Al, etc.

5. Waste water

    a. Main components
        pH, EOD, COD, SS, n-Hex, Phenol, NH_4^+, Cl^-, CN^-, etc.

Results of the experiment include descriptions of:

- Heat and material balance.
- Gas and energy recovery rate.
- Evaluation of the data from public nuisance standpoint.
- Cost estimation.
- Final economics.

From these results, the total process flowsheet for a commercial plant, including pretreatment system was deduced. Thus, the final output allows assessment of the commercial feasibility of the paired fluidized bed pyrolysis unit under pilot plant conditions.

Key words: Baltimore County (MD) Resource Recovery Facility, Cooperative Research (Japan-U.S.), pilot plant scale-up for resource recovery from waste destined for disposal, pyrolysis of refuse derived fuel, refuse derived fuel gasification, solid waste management, waste-to-energy systems.

Gasification of Refuse Derived Fuel in a

Paired Fluidized Bed Pyrulysis Unit

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Government of Japan

In cooperation with Ebara Corporation, Japan

This work described in this report and the gasification experiment were carried out in response to the--Tentative Agreement for Joint Research Japan-United States, December, 1981.

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1. Background

The Agency of Industrial Science and Technology (AIST) in the Japanese Ministry of International Trade and Industry (MITI) has been a strong advocate of the National Resource Recovery System R&D program since its inception in 1972. In 1978, as the final phase of this program the pilot scale plant "Stardust '80" was constructed in Yokohama. Since 1979, many demonstration operations including several periods of long-term operation, mostly using municipal solid wastes from Yokohama as input material, have been performed successfully.

The goal of the program was to develop and demonstrate resource recovery methods and equipment which would represent best possible technology for pollution control, safety and maintenance, which would also allow for economically efficient recovery of resources. This goal has been largely achieved; the technology which has been developed is now ready for commercialization.

Nevertheless, the location and profitable exploitation of suitable markets for the recovered resources is the next challenge which must be dealt with satisfactorily. The viability of a resource recovery system is largely dependent upon market capacity and selling price of the recovered resources. Thus, part two of the tentative agreement for joint research, Japan--United States (December, 1981) calls for the application of National Bureau of Standards resource recovery marketing and planning models.

2. Introduction

(1) Outline of Stardust '80 Yokohama Plant

"Stardust '80 (Yokohama Plant) was operated in the fiscal year 1979-1980[1] as a materials recovery prototype system meant to recycle such useful resources as compost, pulp, fuel gas and light-weight aggregates from municipal refuse. (Material Recovery System -MRS- operation). Since April, 1981, energy recovery systems have been in operation--in both Yokohama and Tokyo--to recover methane gas and fuel oil. (Energy Recovery System--ERS--operation).

Fact Summary for Two-Bed Pyrolysis Gasifier of Stardust '80 Yokohama Plant:

Opening:	May 1979
Principals:	Agency of Industrial Science and Technology M I T I (Owner) Designer and Operator: Ebara Corp.
Volume:	Design and actual; 24,000 kg per day in three shifts 52,800 lbs or 26 tons

[1] The fiscal year in Japan begins on April 1.

Technology: Pyrolizer, dust collector, heat exchanger, gas refiner and waste water treatment plant.

Products: Fuel, gas, electricity and steam.

Cost: $3 Million (1978 basis).

(2) Process flow of pyrolysis system

The pyrolysis gasification system consists of a pyrolysis reactor and combustion reactor. A fluidizing medium (sand) is circulated between two towers; the system is designed to perform pyrolysis and combustion separately, for which reason it is called "Two-Bed Type Pyrolysis."

Figure 1 shows the process flow. The input stock material is fed into the pyrolysis reactor, and the fuel gas generated by pyrolysis reaction is sent into the gas holding chamber after undergoing char-separating, heat-exchanging and gas cleaning processes. A portion of the resulting gas is recycled to the reactor for utilization as fluidizer gas.

Meanwhile, the char (carbonized substances) generated in the reactor is sent together with the sand to the combustion reactor, where air is blown in to aid combustion. The remaining char, which accompanies the pyrolysis gas, is intercepted and separated by means of a two-stage cyclone. The material is also burned in the combustion reactor, where its energy contribution is utilized as a source of heat. The resultant energy generated by combustion is transferred to the sand, which is then recycled to the pyrolysis reactor.

The pyrolysis gas passing through the heat exchanger is cleansed of oil, precipitated carbon bearing particles and noxious gases by means of a spray tower and a scrubber. The scrubbing water is sent to the waste water treatment unit where, after removal of harmful substances, it is discharged into the local sewer system. All of these operations are controlled by means of a centralized system.

The exhaust gas generated by the combustion reactor is discharged into the atmosphere after being treated by means of a two-stage cyclone and an electrostatic precipitator. The non-combustible substances contained in the input stock material are discharged from the bottom of the combustion reactor periodically.

Features of Main Equipment Components

(i) Stock Material Feeder

The RDF is sent to the input stock material feeder (screw type) from the storage silo by means of a constant rate feed mechanism: the stock material feeder is of the solid-overflow type so that the stock material usually can be kept at a constant level. No bridging problems have been encountered to date with this system.

The feeder unit has two-stages with a taper-type feeder followed by a straight-type feeder which prevents gas leakage and also prevents the stock material from being cracked at a low temperature. Therefore, even plastics, which previously were difficult to introduce properly, can be inserted very smoothly and at a constant rate.

(ii) Reactor Body

The pyrolysis reactor and the combustion reactor are connected by two pipes, which allows the fluidizer sand to circulate between the two reactors. The temperature of the fluidizer sand, which has undergone some reduction due to the endothermic thermal cracking reaction occuring in the pyrolysis reactor, is sent to the sand ejector together with whatever char is simultaneously formed. This char reacts with the air stream introduced to blow the sand up to the combustion reactor for burning; thus, the temperature of the sand is raised. This hot sand is circulated back into the pyrolysis reactor.

The sand circulation rate can be controlled satisfactorily by merely injecting a small amount of air into the ejector section. During operation, sand circulation rates ranging from 20 to 30 tonnes per hour have been maintained. In addition, the difference in temperature between the upper and lower parts of the fluidized bed can be stabilized to within ±2 °C, thus providing for a very stable thermal field. The resultant pyrolysis gas has exhibited high uniformity with few fluctuations in composition.

Incombustibles in the input stock material can be easily separated and discharged by means of the air classifier stream. The small amount of sand which is discharged along with these incombustibles can be reintroduced into the combustion reactor after the separation is accomplished.

(3) Experiment

An RDF gasification experiment was performed under the following conditions;

Place:	Two-Bed Pyrolysis Gasification Subsystem in Stardust '80, Yokohama Plant. (Yokohama City, Kanagawa Prefecture)
Time:	November 9-11, 1982
Stock material:	RDF (fluff) - 33.5 metric tons. Produced in Baltimore County's Resource Recovery Facility, in Maryland, U.S.A. This material was provided through the National Bureau of Standards. The entire amount was disposed via gasification during the above mentioned three-day period.

(4) Schedule

On October 28, 1982, 33.5 tonnes of RDF were received and placed in the storage pit of the Stardust 80 resource recovery pilot plant. This RDF was confirmed to be in good condition (no fermentation), despite the long transit time between the U.S. and Japan.

A pyrolysis gasification experiment was carried out for three days as follows:

November 8	Heat-up operation of reactor bodies
9-11	Pyrolysis gasification experiment
11	Blow-down operation

(5) Operating conditions

Table 1 lists important operating parameters for this experiment.

Table 1

RDF feed rate	700 - 1200 kg/hr	1540 – 2640 lbs/hr
Pyrolysis reaction temperature	640 - 680 °C[a]	1184 – 1256 °F
Combustion reactor temperature	700 - 740 °C	1292 – 1374 °F
Both reactors maximum pressure	600 - 1000 mmAq-gauge	23.6 – 39.4 in H_2O .8 – 1.7 psig
Fluidizer sand circulation rate	25 - 30 tonnes 1 hr	

[a] This range has been found to include the most suitable temperature for recovering energy from refuse.

3. Experimental Results

(1) Properties of products and residues

(a) Pyrolysis product gas

Table 3 lists the concentration of the pyrolysis gas recovered in this experiment, and figure 2 shows the relation between pyrolysis reaction temperature and gas composition produced from RDF.

The maximum calorific value of the pyrolysis gas from the U.S. RDF was equal to the that of the gas produced by the MSW of Yokohama City. Pyrolysis gas yield is about 0.5 Nm^3/kg-dry RDF in the temperature range 650 °C to 670 °C; higher temeratures yield more H_2, CO and CH_4 rich gas and less CO_2 rich gas.

The pyrolysis gas contains several potentially harmful gases. Table 4 shows the concentrations of such gases before and after scrubbing of the pyrolysis gas. These potentially harmful gases can be minimized by alkali cleaning and water cleaning. The product gas can then be used in power plants and other industrial applications where medium BTU clean fuel gas would be economically advantageous.

(b) Exhaust gas

Table 5 lists the components and concentrations of the combustion reactor exhaust gas along with the values specified as standards for incinerator exhaust gas in Japan. The concentrations of the potentially harmful gases without gas cleaning and without additives for the elimination of HCl are lower than the incinerator exhaust standard values. Moreover, the results confirm that the present system contains intrinsic low-NOx-producing capabilities. This capability occurs, in our view, because the temperature of the combustion reactor is lower than that of conventional incinceration systems.

Therefore, water was added to the RDF in order to increase its bulk density, and the RDF moisture content was thus raised to 35%.

With regard to HCl gas concentration, satisfactorily low levels were maintained without adding the HCl gas absorbent $Ca(OH)_2$. Amounts of heavy metals are also satisfactorily low. Most of the heavy metals in the RDF reported to the ash.

(c) Ash

Tables 6 and 7 respectively list the ash components and extraction procedure test results for the ash collected by the cyclone and the electrostatic precipitator. Since the content of heavy metals in the Baltimore County RDF is low, most of the heavy metals reported to the ash. Each of the heavy metal values as determined in this experiment satisfies Japanese Government mandatory requirements.

The ash ignition loss in weight is 1.9%; no unburned residue could be found in the incombustibles discharged from both reactors.

(b) Waste Water

Table 8 lists the properties of raw and treated waste water resulting from this experiment. The waste water treatment system employs various physical-chemical treatments such as oil/water separation, solid/liquid separation, stripping, filtration, activated carbon adsorption, etc. The raw waste water has some organic contaminants (see BOD and COD) that exceed 1 percent, but the concentrations of the heavy metals fully satisfy the standards for Japan even in the raw waste water.

As a result, the treated water easily satisfies the requirements set forth in the Kanagawa Prefecture Sewage Ordinance. This water was therefore discharged to the local sewer system.

Table 2 lists the composition of the RDF provided for use in this experiment:

Table 2. Composition of RDF

			RDF
Moisture content[a]		%	14 ~ 20
Bulk density		t/m^3	0.07 ~ 0.09
Calorific value		Kcal/Kg	4650 (gross); 8370 BTU/lb 3690 (net); 6640 BTU/lb
	C		38.6%
	H		5.7%
Ultimate analysis	O		44.7%
	N		0.8%
	S		0.17%
	Cl		0.23%
	Ash		9.8%
	Paper		66.7%
	Textile		21.3%
	Plastics		9.3%
Composition	Yard waste		2.2%
	Metals		0.5%
	Glass		0%
	Garbage		0%

[a] An inclined vibration conveyor, which is incorporated in the refuse transfer line which was intended to carry the RDF from the storage pit to the gasification site refuse silo, could not be used to transfer the RDF (bulk density: 80hg/m^3) because this conveyor is designed to deal with much heavier refuse (bulk density: around 250hg/m^3).

Table 3. Properties of pyrolysis product gas

Component		concentration (%)
H_2		15.3 ~ 16.2
N_2		1.9 ~ 3.9
CH_4		12.9 ~ 16.2
CO		32.0 ~ 34.6
CO_2		17.5 ~ 22.9
C_2H_4		4.5 ~ 6.0
C_2H_6		2.8 ~ 3.0
C_3 - Hydrocarbons		3.3 ~ 3.7
C_4 - Hydrocarbons		1.3 ~ 2.0
Calorific value	kcal Nm^3	5450 ~ 5850* (gross) 5020~5400** (net)

* 610--655 Btu/ft^3
** 560--605 Btu/ft^3

Table 4. Potentially harmful gas phase constituents in product gas

Components	Before scrubbing	After scrubbing
H_2S	520	150
SO_x	230	<10
HCN	711	14
NH_3	142	<10
HCl	790	16
NO_x	Not detected	Not detected

unit: ppm

Table 5. Properties of exhaust gas

		Concentration	Incinerator exhaust standard value
Main gas	O^2	7.5%	
	N^2	81.4%	
	CO^2	11.1%	
Harmful gas	HCl	152 ppm	<430
	NOx	76 ppm	<250
	SOx	<10 ppm	<300[a]
Heavy Metals etc.	Soot dust	0.06 g/Nm^3	<0.1
	Cd	<0.01 mg/Nm^3	<0.5[b]
	Pb	0.37 mg/Nm^3	<10[b]
	Cu	0.15 mg/Nm^3	
	T-Cr	0.02 mg/Nm^3	
	T-Hg	<0.01 mg/Nm^3	
	As	<0.01 mg/Nm^3	

[a] Stipulated K value (K = 1.17).

[b] General smoke emission standard values.

Table 6. Ash components

Components	Concentration (%)	Components	Concentration (%)	Components	Concentration (ppm)
C	1.1	Na	2.3	Cu	840
H	<0.3	K	1.1	Pb	84
N	<0.3	Ca	0.32	Cd	6
S	<0.03	Al	5.9	T-Hg	0.01
Cl	0.28	Ignition loss in weight	1.9	T-Cr	120
				As	2.9

Table 7. Extraction procedure test value of ash

	Concentration	Standard value
Cd	<0.01	<0.3
Pb	<0.1	<3
As	<0.05	<1.5
Cr^{6+}	<0.05	<1.5
T-Hg	<0.0005	<0.005
R-Hg	Not detected	Not detected
Org-P	<0.01	<1
PCB	<0.0005	<0.003
CN-	<0.1	<1

unit: mg/l

Standard values for landfilling in Japan.

Table 8. Properties of raw and treated waste water

	Raw waste water	Treated waste water	Standard value[a]
pH	8.0	7.3	5.7 ∿ 8.7
BOD [mg/ℓ]	18,000	50	<300
COD "	14,000	90	----
Suspended Solids	690	19	<300
Phenols "	1,100	<0.05	<0.5
Cd "	0.03	<0.01	<0.1
CN- "	20	<0.1	<1
Pb "	0.1	<0.1	<1
T-Hg "	0.0006	0.0005	<0.005
Cu "	<0.1	<0.1	<1
T-Cr "	<0.05	<0.05	<2
n-Hexane "	230	<5	<5
NH_4^+ "	340	136	----
Cl "	1,200	900	----

[a] Requirements set forth in Kanagawa Prefecture Sewage Ordinance.

(2) Mass and heat balances

Figures 3 and 4 illustrate the mass and heat balance relationships obtained in this experiment. As shown in figure 3, 317 Nm of medium BTU fuel gas was produced from 1139 kg (moisture content 35 percent) of RDF in one hour. The gross calorific value ranges from 5450 ∿ 5850 Kcal/Nm^3 in the pyrolysis reaction temperature range of 640 ∿ 680 °C. The experimental results indicated that 191 Nm^3 fuel gas and 280 kg (6 kgf/m^2) steam could be recovered as products which could in turn be supplied to some external location.

Details concerning mass and heat balance can be outlines as follows:

Gasification rate[1]	51.3 % (Kcal-gas/Kcal-RDF)
Gas energy recovery rate	30.5 % (Kcal-gas/Kcal-RDF)
Total energy recovery rate[2]	36.2 % (Kcal-gas.steam/Kcal-RDF)

[1] Gasification rate = $\frac{\text{calories of dry product gas}}{\text{calories of dry RDF}}$

[2] Total energy recovery rate = $\frac{\text{total recovered calories of gas and steam}}{\text{total colories of RDF}}$

Experimental factors affecting the observed energy recovery include the following as there were virtually no incombustibles in the RDF:

(i) operations meant to separate and discharge the incombustibles from the pyrolysis reactor were not necessary and

(ii) discharging the high temperature fluidizer sand (including some incombustibles) from the combustion reactor was also unnecessary. Therefore, typical input energy requirements for the reactor were reduced and a significant amount of auxiliary fuel gas (product gas) was thereby saved.

To correct the results of the energy recovery rate computed for typical input RDF with a 15 percent moisture content (as mentioned before, moisture was increased to around 35 percent by the need to add water to the RDF) we used the following values: Gas energy recovery rate 38.1 percent (Kcal-gas/Kcal-RDF); Total energy recovery rate 43.8 percent (Kcal-gas.steam/Kcal-RDF).

(3) Utilities

Table 9 lists the operating costs of this gasification experiment.

Since the pilot plant was designed for the purpose of research and development with respect to gasification technology:

1. Some equipment in the system, such as compressors and blowers, has built-in excess capacity meant to cope with unusual experimental conditions, e.g., aimed at the determination of the upper limits of the system's operational capabilities.

2. In the waste water treatment system, physical-chemical treatment facilities had to be employed instead of less costly biological methods because of the long shutdown intervals occasioned by the irregular testing schedule for Stardust 80. (With biological treatment systems, it is difficult to maintain the function properly while the system is not in operation).

The right hand column of table 9 therefore shows our estimate of operating costs corrected to conform to optimal conditions.

Table 9. Utilities and operating costs

	Consumption per hour	Cost in yen per refuse ton	Corrected cost in yen per refuse ton
Electricity	340 kWH	5,236	2,510[a]
Water	4 m^3	1,080	1,080
Town gas[b]	2 Nm^3	316	316
Nitrogen gas	0.7Nm^3	210	210
Sand	15 kg	150	150
Chemicals for boiler	1 kg	800	800
25 % NaOH	9.4 kg	348	348
35 % H_2SO_4	6.5 kg	410	410
1 % coagulant	6.1 kg	134	134
Activated carbon	30 kg	9,750	270[c]
$Ca(OH)_2$	0 kg	-----	-----
Nourishing salinity	0 kg	-----	20
Total	-----	18,434	6,348

[a] Since 52% of the electricity can be generated by a gas engine (see description below) using recovered fuel gas, the purchase of only 163 kwh of electricity is needed.

[b] Town gas is used for the pilot flame of the auxiliary burner.

[c] With the physical--chemical treatment large amounts of activated carbon are consumed, but in the case of the biological treatemnt, almost all of them are saved.

Gas engine generator

Since 1980, the gas engine generator has been operated for more than 1,000 hours using over 70,000 Nm^3 of recovered fuel gas. We have confirmed that the gas recovered was sufficiently clean and high in calorific value to use for the gas engine, and that the efficiency of energy conversion was as high as 35%. The gas engine employed in the Stardust '80 Plant is a slightly modified standard diesel engine, the main specifications for this engine are as follows:

Type	4 cycle, water cooled, vertical type
Cylinders	6--150 X 165
Generating power	300/1800 PS/RPM 200 kw

4. Implications of scale-up to commercial plant size

(1) Process and scale

In this section, computations describing the expected characteristics of a commercial-scale plant based on the Stardust '80 resource recovery system are discussed.

Calculations for the following two cases were performed by means of a modified computer program which was developed on the basis of the previously described gasification experiment.

Case 1: Pyrolysis gasification plant (including gas engine generator) stock material: RDF 1000 tonnes/day (produced in the U.S.). In this case, RDF is gasified with the same process as that of the Stardust '80 Plant.

Case 2: Pyrolysis gasification plant (including pre-treatment system and gas engine generator) stock material: Municipal Solid Wastes from the U.S.: 100 tonnes/day. Fig. 5 shows the schematic process flow of case 2.

In both cases, required electric power is assumed to be supplied by a gas engine generator fed by product gas from the gasification process.

In both cases, all the raw waste water coming from the product gas refiners is assumed to be burned in the combustion tower.

MSW is separated into two parts (group A and B) by a selective pulverizing classifier, see Appendix 2). After the ferrous metal is removed, group B is shredded to a size less than 150 mm and fed to the reactor, where it is gasified. A fraction of the product gas is consumed by the gas engine generator to meet all demands for electricity in the plant.

The material in group A is assumed to be discharged as residues to be landfilled together with the incombustibles (glass, metals, etc.) discharged from both reactors.

Table 10 lists the results of separation of U.S. municipal refuse predicted by the SPC simulation model. This model was developed on the basis of the results of the processing of over 20,000 tonnes of Japanese MSW taken from various sources. The calorific value of the group B refuse is calculated as 4,600 Kcal/kg-dry (gross) or about 8300 BTU per pound.

Table 10. Results of separation of U.S. municipal refuse predicted by Selective Pulverizing Classifier simulation model

	Input refuse[a]	Group A	Group B
Paper	42.7	28.1	51.7
Glass	11.1	47.0	3.1
Metal	11.1	1.1	3.0
Plastics	9.9	0.7	13.5
Rubber	3.3	0	4.5
Textile	5.9	0.1	8.1
Wood	11.9	8.6	14.2
Garbage	3.5	13.6	1.3
Others	0.6	0.8	0.6
Total	100	100	100
Fraction	100	18.8	72.9[b]
Moisture	19.0	24.2	19.4

unit: %

[a] Municipal solid waste of Baltimore County Md.

[b] The remaining 8.3% is recovered as ferrous metal by magnetic separators.

(2) Predicted gas and energy recovery rates

Figures 6-9 show the mass and heat balances applicable to case 1 and case 2, respectively. The efficiency of the plant for each case was computed to be:

	Case 1	Case 2
Gasification rate	52.8 %	47.1 %
Gas energy recovery rate	43.6 %	35.1 %
Total energy recovery rate	57.1 %	40.5 %

Tables 11-13 list the results of the calculations applicable to required utilities, recovered materials, site area, personnel and capital costs.

Table 11. Utility Requirements

	Case 1	Case 2
City water (t/d)	969	560
Industrial water (t/d)	1790	1620
Chemicals ($Ca(OH)^2$) (t/d)	5.3	8.3
Sand[a] (t/d)	4.8	7.4

[a] Average particle size is 0.56 mm.

Table 12. Recovered materials

	Case 1	Case 2
Fuel gas[a] (Nm^3/d)	305×10^3	172×10^3
Steam[b] (t/d)	811	407
Ferrous metal (t/d)	0	70.5

[a] Calorific value of product gas
Case 1: 5650 kcal/Nm^3 (630 Btu/ft^3)
Case 2: 5500 kcal/Nm^3 (620 Btu/ft^3)

[b] Steam pressure: 16 kgf/cm^2

These volumes of fuel gas and steam are those predicted to be recovered after all other plant energy demands (including electricity) have been taken into account.

Table 13. Capital cost and personnel for operation and daily maintenance

		Case 1		Case 2		
		Pyrolysis system	Gas--engine	Pre-treatment system	Pyrolysis system	Gas engine
Capacity of total system		RDF 1000 t/d		MSW 1000 t/d		
Capacity of pyrolysis system		250 t/d x 4 trains		243 t/d x 3 trains		
	Equipment	24,326	3,100	6,562	33,077	3,078
Capitol cost (x $10^3$$)	Construction	16,956	400	4,298	15,032	400
	Semi-total	41,282	3,500	10,860	48,109	3,478
	Total	44,782		62,447		
Personnel	Operator	4	1	2	3	1
for	Laborer	6	0	3	5	0
operation	Crane man	0	0	2	0	0
and	Shifts/day	(3)	(3)	(2)	(3)	(3)
maintenance (person)	Total/day	33		41		
Necessary site area for construction		36,000 m^2		43,000 m^2		

Appendix 1

Pretreatment Subsystem

The pretreatment subsystem handles such operations as the weighing, receiving, storing and classifing of the collected refuse mixture so as to supply each backend subsystem with stock material. The main equipment in the pretreatment subsystem is the selective pulverizing classifier (SPC).

The classifier has a circular shape and is approximately 3 meters in diameter and about 8 meters in length. The input refuse mixture, delivered by conveyor is fed into the classifier, where the refuse is classified via passing through a trommel. The classified refuse is dropped out onto other conveyor belts provided below the classifier and carried to each subsequent subsystem. This equipment comprises a cylindrical rotary screen drum and a pulverizing scraper plate. The latter is incorporated into the former but rotates at a speed different from that of the rotary screen drum. Thus, the refuse is pulverized and classified simultaneously.

The first items of input refuse to be pulverized and classified with the rotary screen drum are garbage, soil and sand and glass and chinaware, all of which are relatively brittle; the refuse so classified is referred to as Group I material. The remainder of the refuse passes through the screen drum; water is sprayed onto the refuse at the center of the pulverizing scraper plate in the second screen drum. This water is absorbed by paper and other materials in the refuse. The resulting mixture has lower impact resistance and shearing force than the dry material. Thus, the mixture can easily be pulverized on the pulverizing scraper plate and selectively discharged from the second rotary screen drum. The material so discharged is referred to as Group II. The remaining refuse consists of plastics, metal cans, etc., which are highly resistant to impacts and shearing forces.

This material is referred to as Group III and is discharged at the furthermost end of the drum. Table "a" lists the refuse components as classified by means of the selective pulverizing classifier.

Table a. Example of separation of municipal refuse by selective pulverizing classifier system.

Refuse contents	Input refuse	Composition after separation Group 1 Fraction	Group 2 Fraction	Group 3 Fraction
Plastics	11.4	0.9	2.9	38.3
Textile	4.1	0.3	1.1	13.8
Wood, bamboo	3.8	2.9	2.0	7.0
Paper	38.5	25.9	81.5	18.0
Garbage	10.9	19.8	5.3	0.5
Straw, leaves	0.8	0.9	0.9	0.4
Leather, rubber	0.5	0.1	0.0	1.5
Metals	5.9	0.6	0.4	20.4
Glass, stone, ceramics	15.0	30.3	2.4	0.0
Dirt; miscellaneous substances	9.1	17.3	3.5	0.0
Total	100.0	100.0	100.0	100.0
Moisture	50.0	63.2	64.8	30.2

The pretreatment subsystem includes the following features:

(a) Capable of simultaneously pulverizing and classifying refuse in a single process and with a low rate of power consumption.

(b) Group I is composed mainly of garbage, which may be used for compost.

(c) Group II is composed mainly of paper, which may be used for pulp.

(d) Group III is composed mainly of plastics, and is thus a favorable feedstock for gasification.

(e) In response to changes in input refuse composition or in requirements for classification, the pretreatment subsystem permits easy alteration of the degree of classification. This control is achieved by changing the feedrate of refuse in the drum and/or the relative velocity of both the pulverizing scraper plate and the drum.

Appendix 2

Selective Pulverizing Classifier (SPC2)

1. Functions

(1) Separation capability: SPC2 can classify municipal refuse into two groups, i.e., compostable materials and non-compostable materials.

(2) Crusher: SPC2 can crush compostable materials in municipal refuse into sizes suitable for aerobic fermentation. Excessive crushing is avoided, because it not only wastes power, but may also rupture dry batteries in the waste could cause heavy metal contamination in the compost.

(3) Bag-breaker: SPC2 can cope with refuse collected in plastic bags or boxes.

2. Features.

(1) SPC2 can be used directly to apply suitable moisture for aerobic fermentation.

(2) SPC2 tends to operate properly even if bulky items such as metal appliances are charged.

(3) Entanglement of long strings around the rotary shaft, a major problem with conventional shredders, is said to be eliminated by the wrap prevention device specifically developed for this machine. This feature renders the manual removal of strings unnecessary and greatly reduces maintenance time.

(4) Unlike conventional trommel type screens, this sieve is unlikely to become clogged because of cleansing function of scrapers.

(5) Because of its very low speed, this classifier creates far less wear, noise and vibration than conventional high-speed shredders. The SPC2 which incorporates both pulverizing and classification by screening in one machine, developed with full support of the Agency of Industrial Science and Technology (AIST of MITI of Japanese government) and was awarded the Directors Prize of the Ministry of Science and Technology in 1977, and the Mechanical Institute Prize in Japan 1978.

3. Brief description of equipment

(1) General. Pretreatment for composting refuse requires three basic functions: 1) elimination of non-compostable materials, 2) size reduction without operating leakage from dry batteries, and 3) moisture adjustment.

1) The elimination of non-compostable materials such as plastics, metals, textiles, etc., from raw refuse before fermentation yields the following important advantages:

   a) The capacity of the fermenter can be increased substantially by the elimination of non-compostables, particularly plastic films and the like, which have a large specific volume.

   b) Heavy metals contained in the non-compostables may dissolve into the compost during the course of the preliminary fermentation, thus lowering the pH value of the final product.

   c) Bulky textiles and long strings contained in the refuse often become entangled in the stirring mechanism of the usual type of fermenter.

2) Size reduction to obtain a large specific surface of the material is preferable for fast fermentation. Excessive pulverization, however, must be avoided, since it not only requires a large amount of power but also ruptures dry batteries leakage from which may cause heavy metal contamination in the compost.

3) The moisture of the pretreated compostable material must generally be kept within a limited range (about 40 to 60% depending on the type of fermenter) which is suitable for aerobic fermentation.

(2) The Selective Pulverizing Classifier (SPC2): Based on the preceding three requirements, the SPC2 (Selective Pulverizing Classifier) was developed. The SPC2 takes advantage of differences in the resistance to destruction of different material; both pulverization and classification by screening can be accomplished with the aid of this one machine. As shown in appendix figure 1, the SPC2 consists of a rotating drum screen and a scraper rotating at a different speed inside the screen.

As the refuse is fed continuously into the rotation drum, almost all of the garbage (food waste) and brittle materials such as dirt, glass and ceramics, and a fraction of the (flimsy) paper are pulverized into particles or flakes and pass through the screen (A Group). The remaining residues consisting of plastics, metals and textiles etc., are discharged through the open end of the drum (B Group).

In the case of dry refuse input, moisture can be increased by spraying water from a tap built into the central shaft so that the optimum water content for fermentation of A Group material can be easily obtained. Additional moisture can also increase the paper concentration in A Group owing to the resultant strength reduction of the paper.

In the case of wet input (considerable amounts of wet garbage), an increase in the relative speed between the drum and scraper produces a considerable increase in the pulverizing effect and in the concentration of dry paper in A Group which in turn decreases its total moisture content.

Unlike the conventional shredder, which completely shreds all the refuse, this classifier discharges B Group materials from the drum end following the process of selective pulverization. This refuse remains close to its orginal size. Almost all of the dry batteries contained in the refuse maintain their original shape and remain sealed.

Small batteries are discharged into the A Group without being shredded. These batteries are separated by the magnetic separator. The size of pieces of glass and ceramics discharged into A Group is extremely large compared with that produced by conventional shredding. These remnants can be easily removed after fermentation.

4. Engineering Aspects.

SPC2 consists of a rotating drum screen equipped with ridge projections, rotating scrapers inside the drum screen, and a drive unit which drives both the drum screen and the rotating scraper by means of one motor protected by a safety device.

The motion of the rotating drum screen is controlled by means of a chain driven by the motor followed by a reduction gear. The RPM value is kept constant within the range of 20 to 40 rpm.

The rotating scraper located inside the rotating drum screen, is controlled by means of a belt driven by the SPC2's single motor and a infinitely variable transmission. The RPM of the rotating scraper is variable within the range of 40 to 80 rpm.

The rotational direction of the scraper is the same as that of the drum screen, but the rotational speed is different. Therefore, shear stress arises and pulverization occurs in the region between the scraper and the ridge projection mounted in the inside of the drum screen.

5. Separation Performance

Table "b" lists test results for separating a sample of municipal refuse with the SPC2. As seen in this table, garbage (kitchen refuse) was concentrated by a factor of about two, and plastics and textiles, the main components of RDF, were almost completely discharged through the open end of the drum as B Group.

Accordingly, the SPC2 was judged to be suitable separating equipment for the plant producing both RDF and compost from municipal refuse. Since the particle diameter of the compostable materials (A Group) from SPC2 is pulverized and homogenized to a size of about 20 to 40 mm, extremely good fermentation can be achieved.

6. Utility Requirement.

Electricity consumption of the SPC2 is 10 to 15kwh/tonne (input refuse).

Table b. Test Result of SPC2

	Municipal Refuse	A Group		B Group	
	Composition (%)	Composition (%)	Classification (%)	Composition (%)	Classification (%)
Paper	56.3	58.1	49.1	55.0	50.9
Garbage	14.5	29.4	96.6	1.0	3.4
Textile	10.0	0.6	3.6	18.5	97.0
Wood	2.6	1.7	31.0	3.4	69.0
Dirt	0.8	1.7	100.0		0.0
Glass	3.3	6.9	100.0		0.0
Metal	8.2	0.8	5.0	14.9	95.0
Plastics	4.3	0.8	10.0	7.2	90.0
Total (Dry)	100.0	100.0	100.0	100.0	
Moisture (Content) (%)	49.3	54.5		40.2	

[a] Each rate of classification described in this table assumes that sewage sludge is not mixed with refuse. Mixing refuse and sludge causes an increase of classification rate of paper in the A Group.

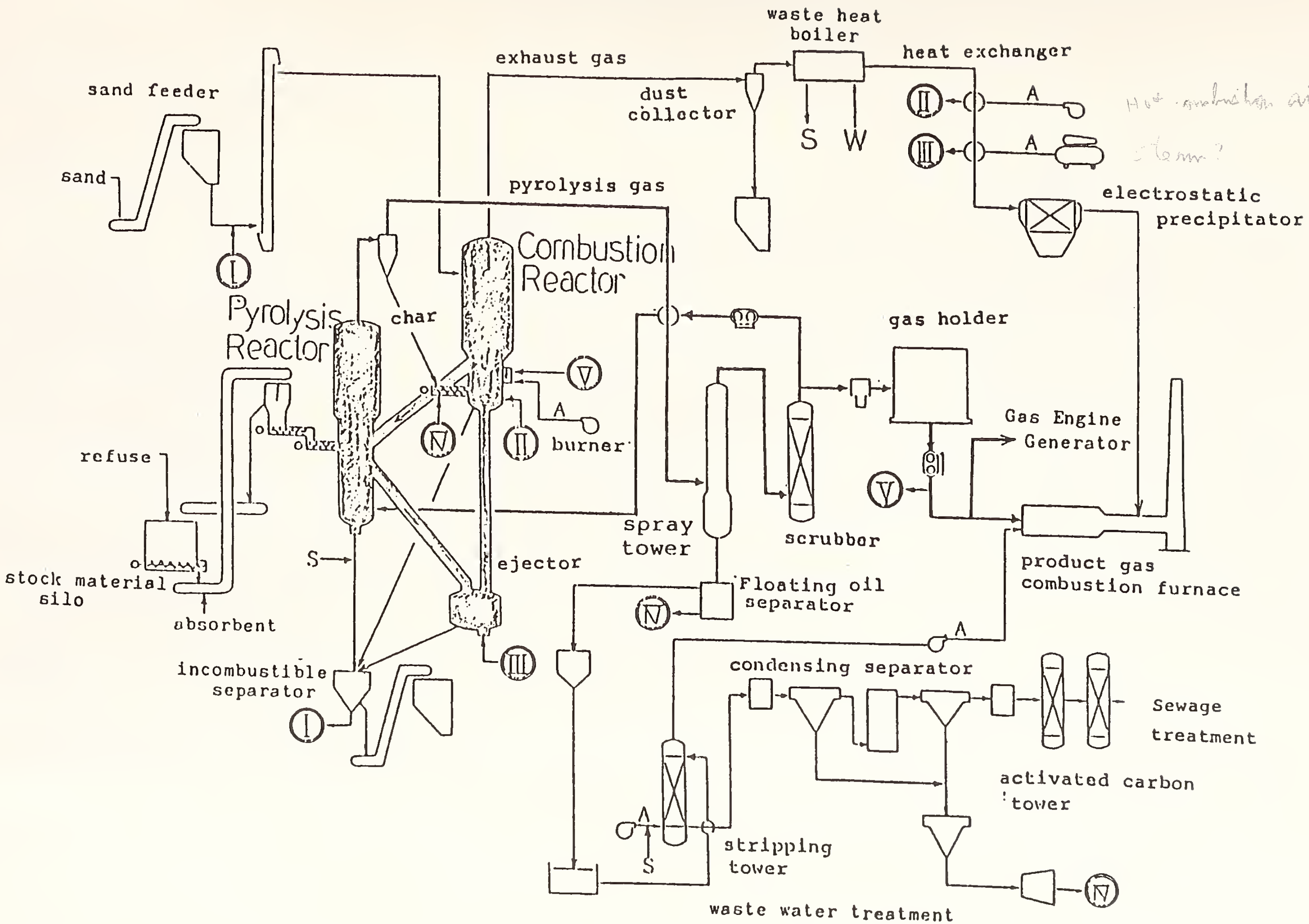


Figure XIII.1. Two-bed pyrolysis system process flow.

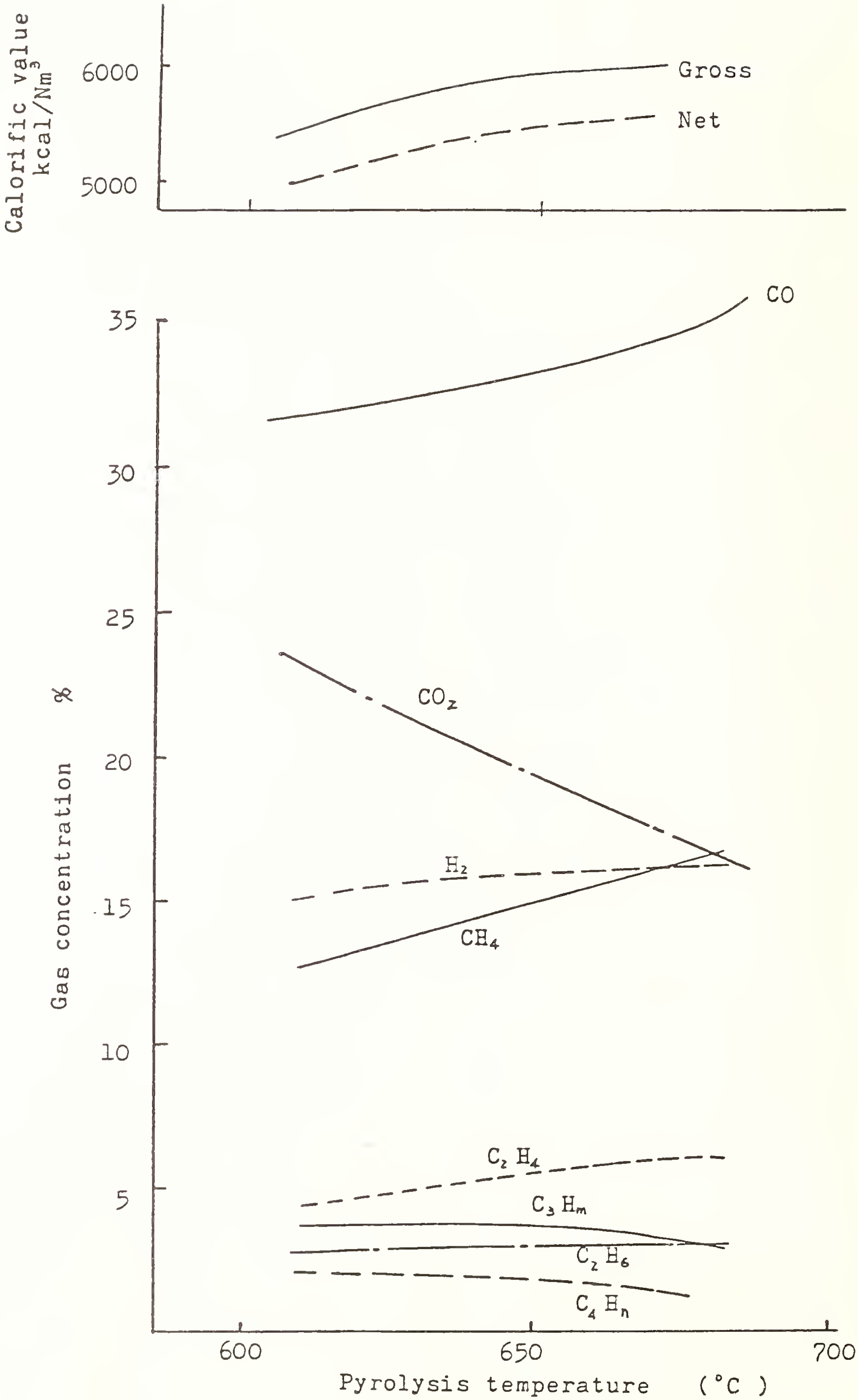
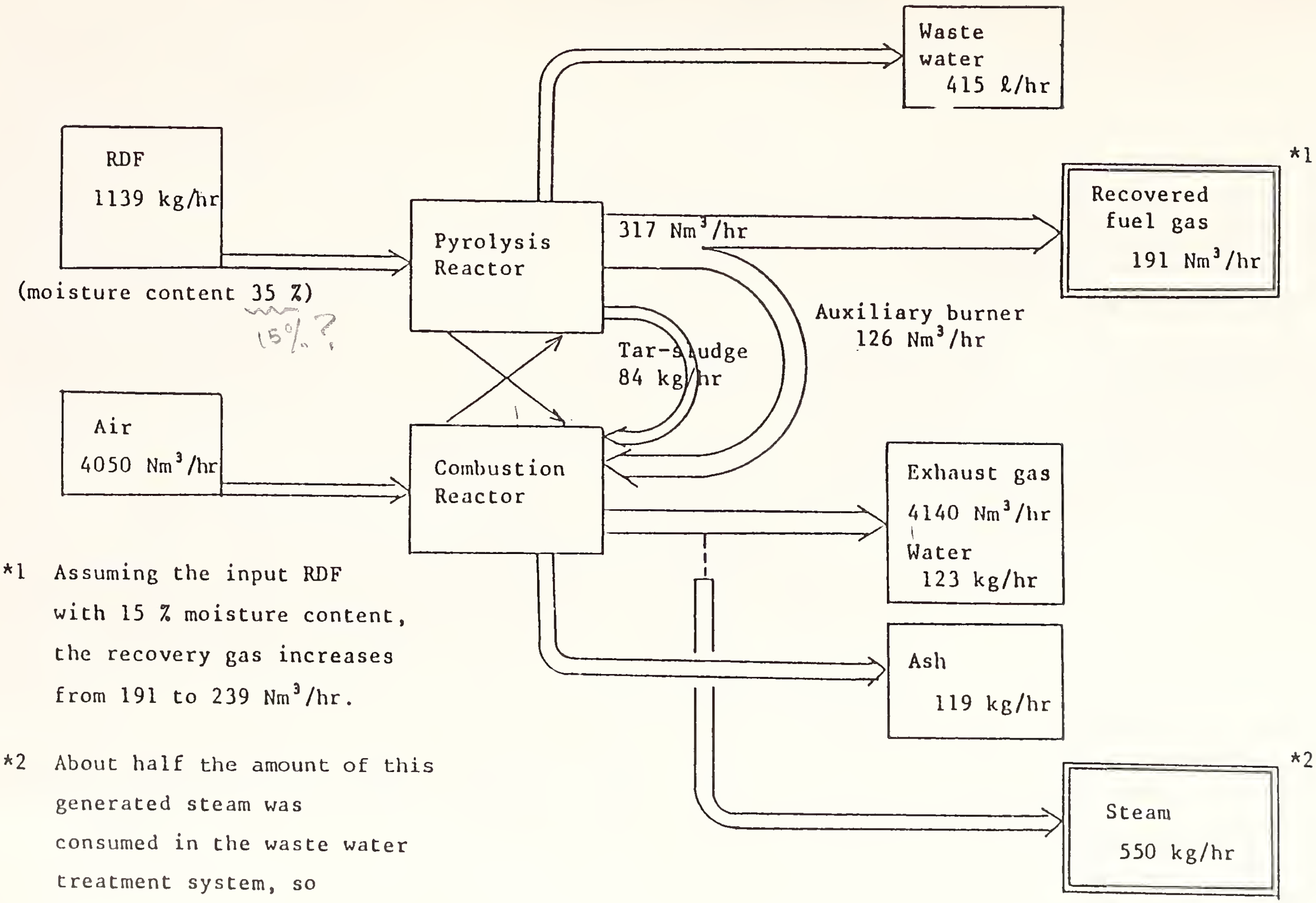


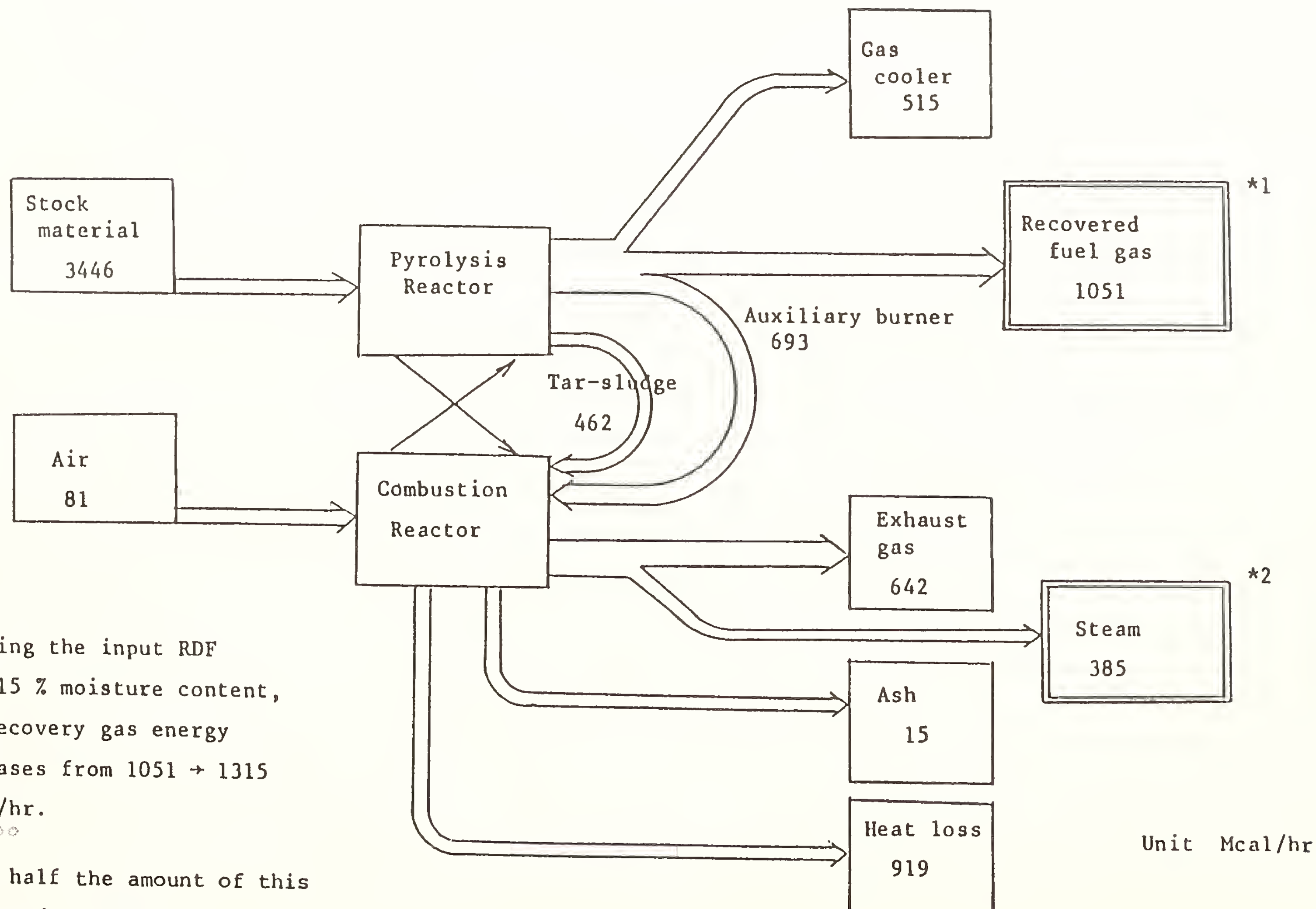
Figure XIII. 2. Gas concentration vs. pyrolysis temperature.



*1 Assuming the input RDF with 15 % moisture content, the recovery gas increases from 191 to 239 Nm^3/hr.

*2 About half the amount of this generated steam was consumed in the waste water treatment system, so 270 kg/hr of steam were ultimately recovered.

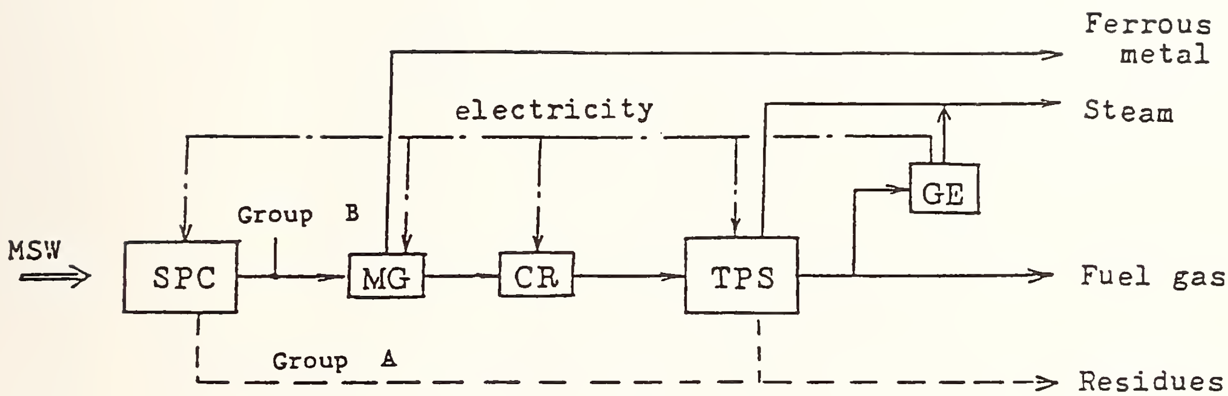
Figure XIII.3. Mass balance.



*1 Assuming the input RDF with 15 % moisture content, the recovery gas energy increases from 1051 → 1315 M cal/hr.

*2 About half the amount of this generated steam was consumed in the waste water treatment system, so 196 M cal/hr of energy were ultimately recovered.

Figure XIII.4. Heat balance.



SPC ; Selective Pulverizing Classifier

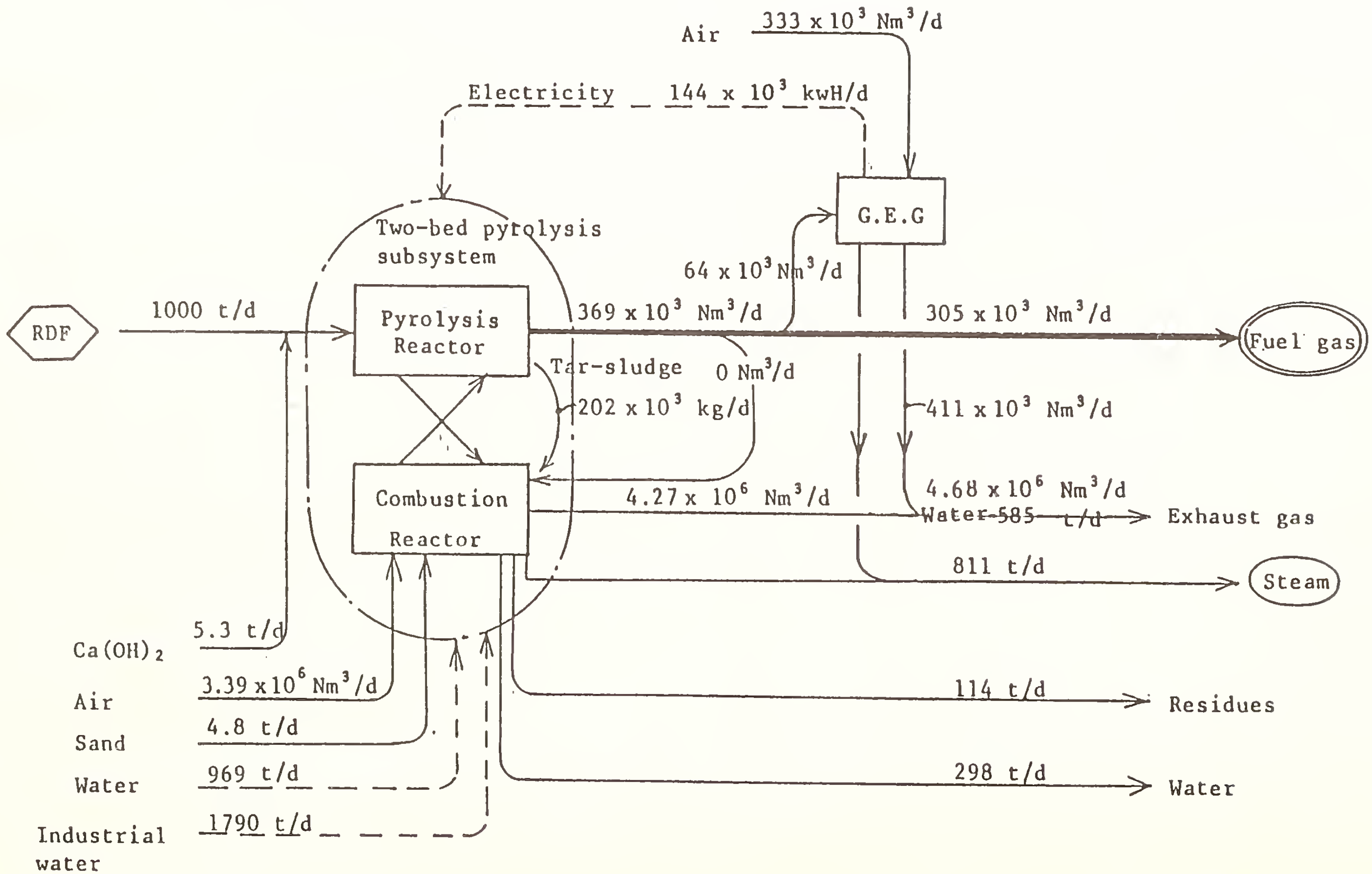
MG ; Magnetic Separater

CR ; Crusher

TPS ; Two-bed Pyrolysis system

GE ;Gas Engine Generator

Figure XIII.5. Schematic process flow.



G.E.G. ; Gas Engine Generator

Figure XIII.6. Mass balance (Case 1).

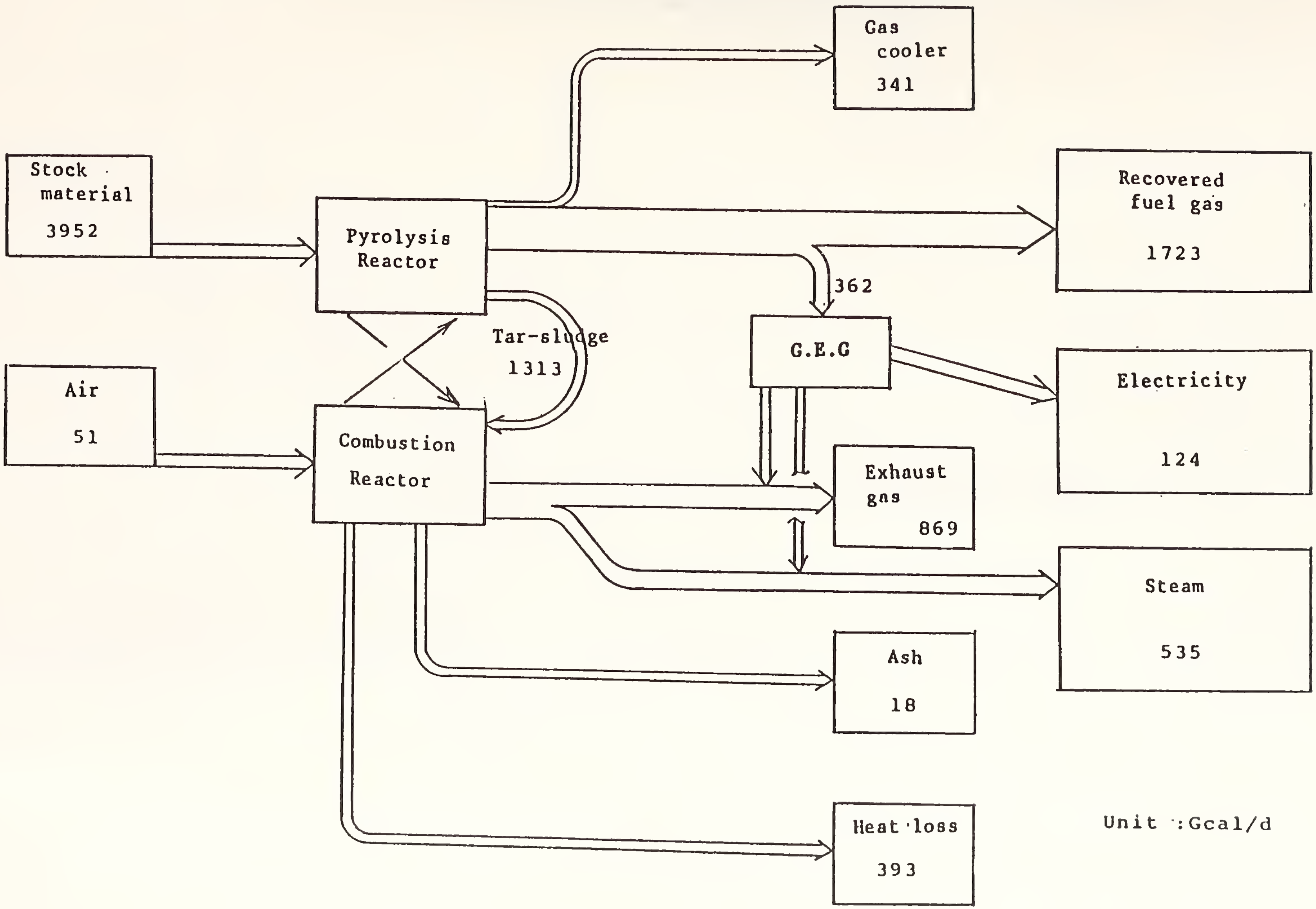


Figure XIII.7. Heat balance (Case 1).

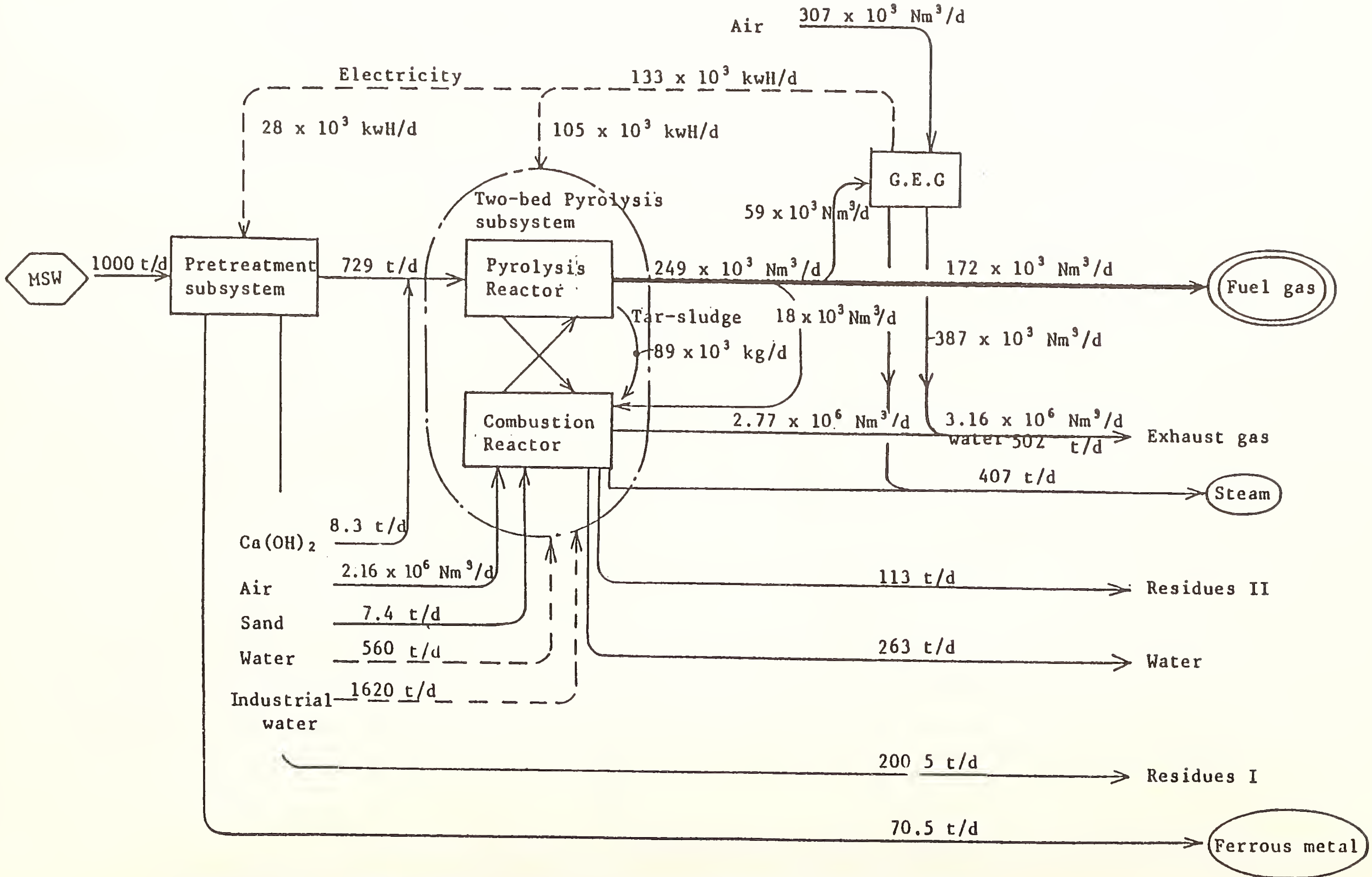


Figure XIII.8. Mass balance (Case 2); (G.E.G. means Gas Engine Generator).

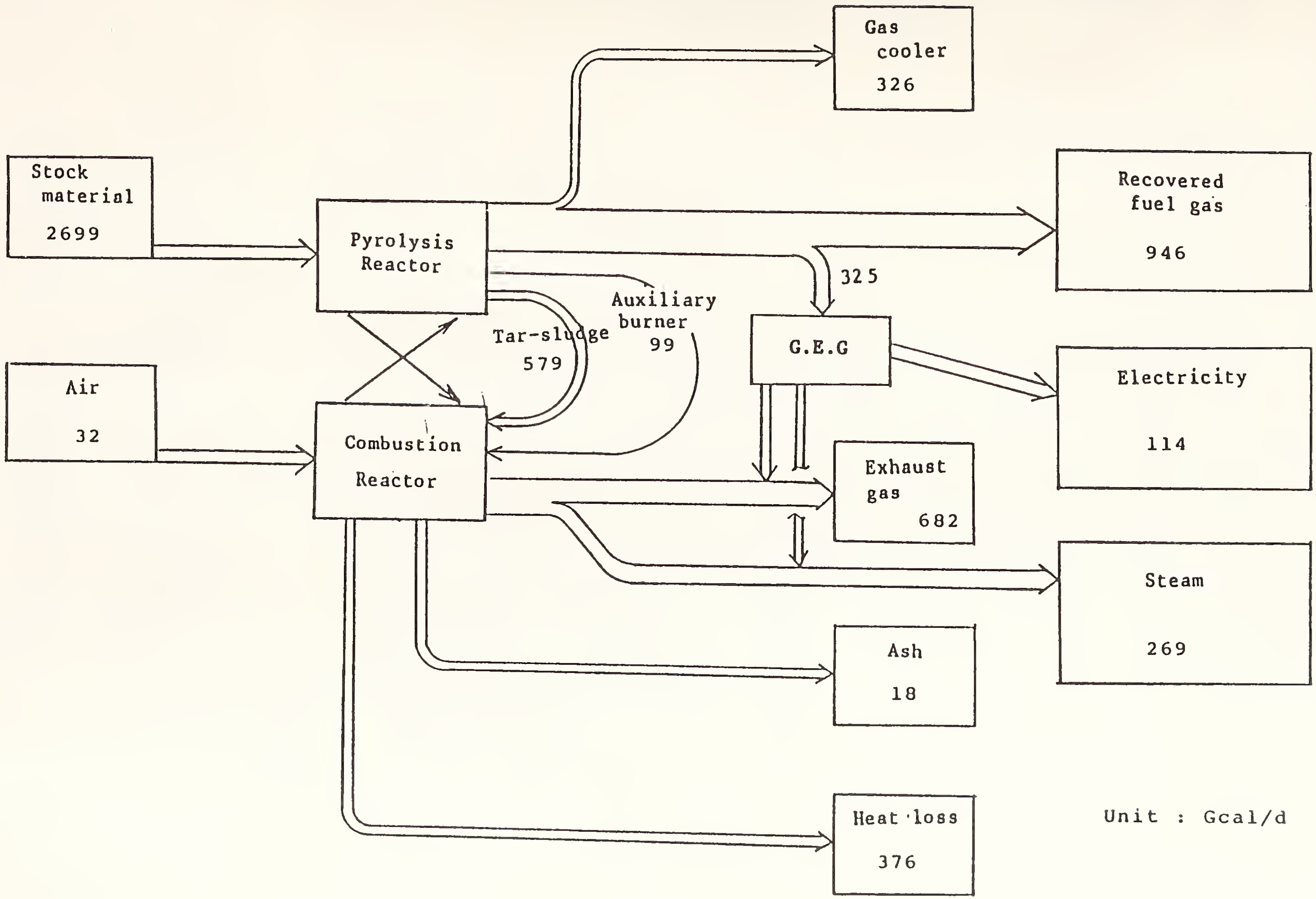
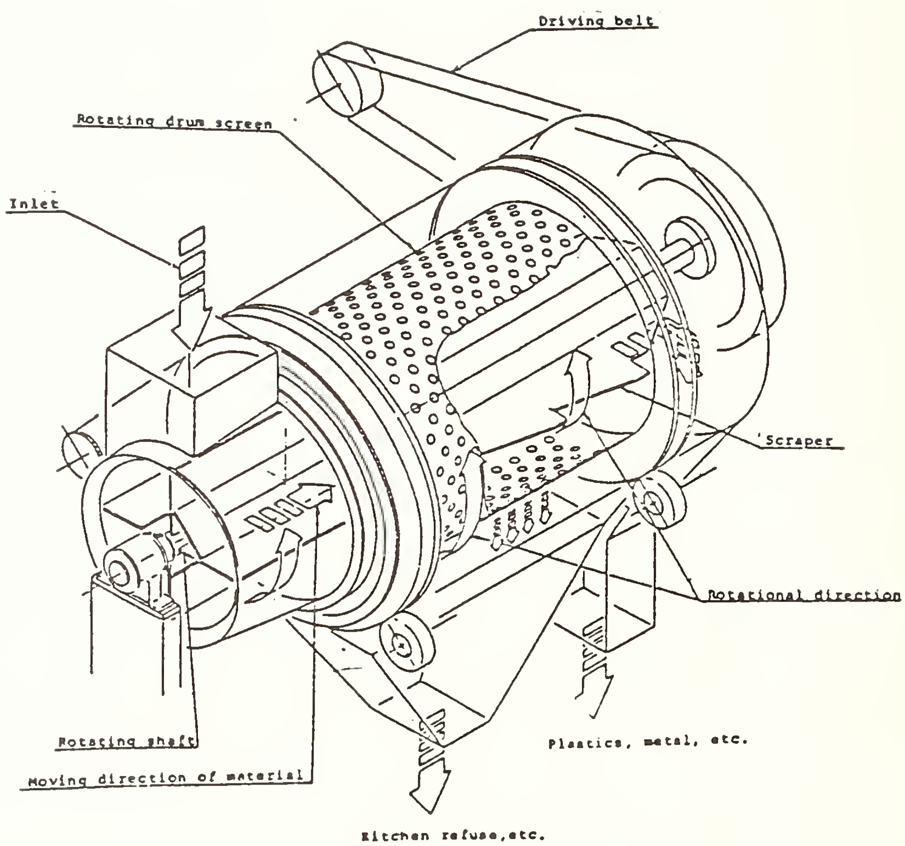


Figure XIII.9. Heat balance (Case 2).



Appendix Figure 1.

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBS SP 664	2. Performing Organ. Report No.	3. Publication Date September 1983

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5. AUTHOR(S)

S. Suzuki (Gov't of Japan)
Harvey Yakowitz (NBS)

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

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10. SUPPLEMENTARY NOTES

Library of Congress Catalog Card Number: 83-600583

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

As part of the scientific interchange program initiated by the United States Government and the Government of Japan, the Department of Commerce was selected by the White House to be the pilot agency for a project concerned with resource recovery from discards originally destined for waste. Such discards include municipal waste and industrial waste. Under terms of the agreement signed by the President and the Prime Minister on May 2, 1980, the United States and Japan will exchange small teams of government scientists in order to examine resource recovery in the respective countries and to formulate possible joint research ventures.

The Office of Recycled Materials of the National Bureau of Standards (NBS/ORM), which was charged with fulfilling the duties assigned to the Secretary of Commerce by Subtitle E of the Resource Conservation and Recovery Act as amended (P.L. 94-580; PL 96-482) was designated as the U.S. contact point for this project. The Japanese team visited the U.S. in December, 1981; NBS/ORM arranged the itinerary and provided technical briefings and an overview of resource recovery activities. At that time, NBS/ORM and Japanese representatives concluded an agreement for joint research to be performed as part of the project. The results described in this report were developed in partial fulfillment of this agreement.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Baltimore County (MD) Resource Recovery Facility; Cooperative Research (Japan-U.S.); pilot plant scale-up for resource recovery from waste destined for disposal; pyrolysis of refuse derived fuel; refuse derived fuel gasification; solid waste management.

13. AVAILABILITY

- [XX] Unlimited
- [ ] For Official Distribution. Do Not Release to NTIS
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